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Aaron B. Shiels
USDA, APHIS, Wildlife Services, aaron.b.shiels@aphis.usda.gov

D. Will
Island Conservation

C. Figuerola-Hernández
Island Conservation

K.J. Swinnerton
Island Conservation & The Island Endemics Foundation

S. Silander
Caribbean Islands National Wildlife Refuge Complex

See next page for additional authors

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Authors

Aaron B. Shiels, D. Will, C. Figuerola-Hernández, K.J. Swinnerton, S. Silander, C. Samra, and G.W. Witmer

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Trail cameras are a key monitoring tool for determining target and non-target bait-take during rodent removal operations: evidence from Desecheo Island rat eradication

A.B. Shiels[1], D. Will[2], C. Figuerola-Hernández[2], K.J. Swinnerton[2,3], S. Silander[4], C. Samra[1] and G.W. Witmer[1]

[1]USDA, APHIS, WS, National Wildlife Research Center, Fort Collins, CO 80521, USA. <aaron.b.shiels@aphis.usda.gov>. [2]Island Conservation, 2100 Delaware Ave, Suite 1, Santa Cruz, CA 95060, USA. [3]The Island Endemics Foundation, P.O. Box 1908, Boquerón, PR 00622, USA. [4]U.S. Fish and Wildlife Service, Caribbean Islands National Wildlife Refuge Complex, Cabo Rojo, PR 00622, USA.

Abstract Efforts to remove invasive rodents (e.g. *Rattus* spp. and *Mus musculus*) from islands often use toxicant-laced baits containing the anticoagulants brodifacoum or diphacinone. Rodenticide baits are generally delivered through aerial- or hand-broadcast, or in bait stations. These baits are not rodent-specific and are subject to non-target consumption or secondary exposure (e.g. an individual preying upon another individual that has consumed bait). During rodenticide applications, it is generally unknown which animals are visiting and consuming bait; and to quantify this, we recommend using trail cameras (e.g. Reconyx™ motion-activated infra-red) positioned to monitor individual bait pellets. To demonstrate the importance and effectiveness of using trail cameras during such operations, we report results of target (*Rattus rattus*, black rat) and non-target (native land crab, lizard, insect) bait-interactions after an aerial-broadcast of Brodifacoum-25D Conservation to eradicate rats from Desecheo Island, Puerto Rico. During the first five days following bait application, trail cameras (n = 15) revealed that there were 40 incidences of animals contacting bait pellets: 50% rat, 32% hermit crab, 13% *Ameiva* lizard, and 5% insect. Trail cameras provide temporal and spatial information regarding the effectiveness of rodent removal, and the last rat pictured by trail cameras on Desecheo was six days after bait application began. Trail cameras revealed 30 incidences of animals contacting bait pellets 6–20 days after bait application began: 47% hermit crab, 37% *Ameiva* lizard, 13% insect, and 3% black crab. Despite viewing ~69,000 images from trail cameras, lizards were never pictured consuming bait on Desecheo; therefore, any brodifacoum exposure to Desecheo lizards likely occurred via secondary pathways (e.g. consumption of contaminated insects). Scaling up, we estimate that > 75% of the total bait distributed on Desecheo was not consumed by rats. Trail cameras help inform the hazards of rodenticide use and can be easily incorporated into rodent removal operations.

Keywords: aerial rodenticide broadcast, best practice methods, brodifacoum anticoagulant, land crabs, motion-sensing cameras, *Rattus rattus*, risk assessment, tropical dry forest

INTRODUCTION

Invasive species, particularly rodents, are among the greatest threats to native biodiversity on islands. The breadth of flora and fauna that have been extirpated, or are currently threatened, by invasive rats (*Rattus* spp.) and house mice (*Mus musculus*) is extensive (*see* Towns, et al., 2006; St Clair, 2011; Shiels, et al., 2014). The most common method to suppress invasive rodent populations, or eradicate them from islands, is by using toxicant-laced baits such as those containing the anticoagulants brodifacoum, bromadiolone, or diphacinone (Howald, et al., 2007; Duron, et al., 2017). These rodenticide baits are not rodent-specific and are subject to non-target exposure through their direct consumption of the bait (i.e. primary exposure) or by an individual preying upon another individual that has consumed bait directly (i.e. secondary exposure). Until there is a rodent-specific toxicant developed that can be effectively delivered to target rodent species, non-target species that co-habit treatment areas where rodenticides are used may be at risk to exposure and possibly death. Therefore, there is a level of risk involved when using anticoagulant rodenticides that is relevant to livestock managers and pet owners in domestic settings, and to conservationists attempting to protect native species from the negative effects of rodents in natural areas (Hoare & Hare, 2006).

Existing methods for rodenticide risk assessments suggest implementation of non-toxic bait-uptake trials with biomarker-laced bait, and rodenticide residue analysis of native fauna, both of which can be expensive and may require harvesting individuals including those that are threatened or rare (Pott, et al, 2015). Bait uptake trials with biomarkers are important to determine the level of non-target exposure to bait, and subsequently help determine the bait application rates needed at the site. However, such trials are not always used for island-wide rodent eradication attempts (Pott, et al, 2015) and rarely used for rodent suppression projects (Duron, et al., 2017), perhaps in part because such trials are not a requirement for use of the rodenticide product, and they necessitate considerable effort associated with the capture and sampling of the target and non-target animal community. Although expensive and requiring the harvest of native animals, rodenticide residue studies revealed that residues of the used toxicant establish throughout most of the biological food web and often result in some non-target animal mortalities (e.g. Pitt, et al., 2015). The general acceptance of risk associated with rodenticide use is based on the premise that benefits to native wildlife outweigh the costs (i.e. native wildlife populations increase despite losing a few native individuals from toxicant exposure). A recent example in Alaska reviewed by Croll, et al. (2016) demonstrates that the short-term loss of some individuals of native birds following a rat eradication using brodifacoum has been overwhelmed by large increases in types and abundances of native seabirds over the long term.

The use of trail cameras (i.e. motion-triggered infra-red cameras) is an underutilised method to assess risk to non-target animals associated with rodenticide use. Trail cameras are a means of continuously monitoring rodenticide bait for animal interactions without having to be physically present for such observations. Human observations of animals visiting the bait during rodenticide applications are rare, due to the inability to watch more than a few bait pellets at once and the great likelihood of missing certain animals because of their unique behaviours during foraging (e.g. being secretive, nocturnal, or confined

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to particular habitats). Trail cameras can be placed across a variety of habitats, installed to monitor bait for long periods (days to months), and reliably record diurnal and nocturnal visitation while not substantially altering behaviours (some animals can hear or see cameras/functions; Meek, et al., 2014) or harming resident animals (Swan, et al., 2004). When monitoring bait exposure to wildlife, trail cameras may be less expensive than other methods that require capturing or harvesting animals, and do not require animal use permits or animal sampling. Furthermore, the nearly real-time evidence of bait consumption by target and non-target species documented by trail cameras provides the operational staff confidence that the target rodents are consuming the bait, and allows for adjustments to any subsequent rodenticide bait applications or non-target mitigation strategies, if needed.

We propose that trail cameras provide critical information regarding target bait acceptance, effectiveness, and primary non-target bait exposure during rodent removal campaigns, and therefore future rodent removal campaigns should consider employing this tool. To demonstrate how trail cameras can be used effectively to meet such goals, we report the results of a field study associated with a rat eradication project on Desecheo Island, Puerto Rico, where bait take by target (*R. rattus*) and non-target animals (native crab, lizard, insect) were assessed after the aerial-broadcast of Brodifacoum-25D Conservation bait (3 g pellets, 0.0025% brodifacoum). We used trail cameras to assess the proportion of bait that rats and non-target species interacted with, including how much they removed or consumed, during each of the bait applications. We were also interested in documenting the spatial and temporal changes in bait interactions, including when rats were no longer observed visiting baits. We expected rats to be early primary consumers of the bait, and their observation would quickly decline one to two weeks after the first bait application. Because of the high densities of hermit crabs (*Coenobita clypeatus*) on many parts of the island, we expected that their role in bait consumption and removal would be formidable and consistent between applications; yet, we expected much less bait removal and consumption from other non-targets, such as the three endemic lizard species that have mostly insectivorous life-histories, and the few forest birds and seabirds on the island.

METHODS

Study site and animals

Desecheo (18°23′14″N, 67°28′19″W) is a small (1.2 km^2 or 117 ha) island approximately 21 km from the western shore of the main island of Puerto Rico. The terrain is rugged with karst limestone as parent material, and the peak elevation is 218 m. Vegetation is *Bursera simaruba*-dominated forest, shrubland, and grassland. Annual rainfall averages 1020 mm (Seiders, et al., 1972). The island is a U.S. Fish and Wildlife Service (USFWS) National Wildlife Refuge. *Rattus rattus* is abundant on Desecheo, and was first reported in 1912 (Wetmore, 1918). The negative impacts of *R. rattus* to natural areas and native species on tropical islands are well known (Towns, et al., 2006; St Clair, 2011; Shiels & Drake, 2011; Pender, et al., 2013; Shiels, et al., 2013; Shiels, et al., 2014); rats on Desecheo have been observed eating juvenile lizards and suspected of consuming other native species (Draft EA, 2015). Desecheo has three endemic lizards (anole: *Anolis desechensis*, gecko: *Sphaerodactylus levinsi*, ameiva ground lizard: *Ameiva desechensis*) that may be vulnerable to rats. Although non-native goats (*Capra hircus*) and non-native rhesus monkeys (*Macaca mulatta*) were once common to the island, they have been functionally eradicated (Hanson, et al., 2019). Prior to military actions and rhesus monkeys being introduced to the island, Desecheo had one of the largest nesting colonies of brown boobies (*Sula leucogaster*) in Puerto Rico.

Bait application

In March/April 2016 (the dry season), USFWS and Island Conservation (IC) conducted the bait application operation on Desecheo using Brodifacoum-25D Conservation (25 ppm brodifacoum in ~3 g pellets), under a supplemental label specific to the 2016 eradication effort (Will, et al., 2019). Bait was applied aerially at 30–45 kg/ha (depending upon habitat; see Fig. 1) for each of two applications (18 March and 9 April) in 2016. The 2016 rat eradication attempt used application rates two to three times greater of Brodifacoum 25-D Conservation than those used in the unsuccessful 2012 eradication attempt.

Experimental design

There were 11 sites on Desecheo established for monitoring (Table 1; Fig. 1). These sites were chosen to occupy the different habitats and bait application regions (e.g. deflector, coastal overlap, valleys, cliff; Fig. 1) in areas accessible (often near established trails) on the western half of the island; the steeply sloped terrain and cliffs were avoided for safety and logistical concerns. In total, we established four sites in the 'interior' on ridges or slopes, two sites in 'valley floor/bottoms', one 'cliff' site, two sites in the 'deflector' zone, which was immediately inland of the water's edge and high tide line, and two sites in the 'coastal overlap', which was the most inland portion of the deflector zone and the adjacent inland zone (i.e. interior or valley floor/bottom). To consistently describe the habitat at each site, slope and vegetation were described by a single person (A. Shiels) measuring three variables at each of the 11 sites (Table 1).

At each of the 11 sites, we established a single 150 m transect that had flags marking each 10 m along the transect. Transects were established with meter tapes in a straight line that roughly paralleled walking trails. Once within at least 150 m of a targeted habitat (i.e. interior, valley floor/

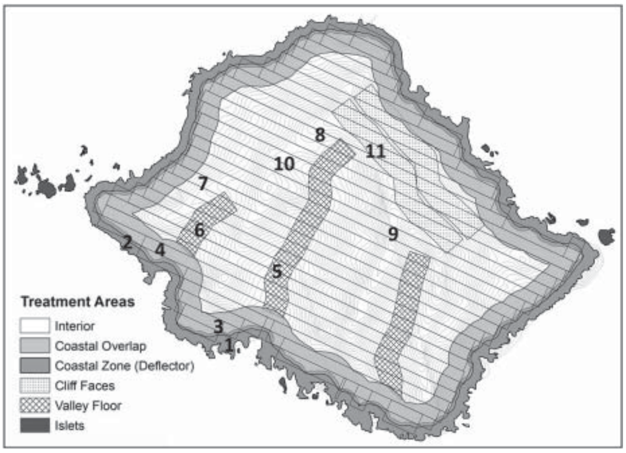

Fig. 1 Map of Desecheo Island, Puerto Rico, outlining the different treatment zones for bait application. The entire island received two applications of Brodifacoum 25D: Conservation rodenticide bait in 2016 (18 March and 9 April). Bait application rates were 30 kg/ha for both applications for all parts of the island except the coastal overlap (#3, #4), cliff faces (#11), and valley floors (#5, #6), which each received a total of 45 kg/ha during both applications. For orientation, there are three main valleys on the island, where (left to right, or west to east) West Valley (containing #6) is the smallest and most western (also where camp was set up at the base), Long Valley is the middle valley (containing #5), and East Valley is the eastern valley. See Table 1 for details of each site.

Table 1 Bait application rates (mean +/- SE bait pellets per m²) and ground cover vegetation (0–1 m height) measured on the ground in 1 m² plots (n = 15 for each site) along 150 m transects on Desecheo Island, Puerto Rico. Target application rates were either 30 kg/ha (equivalent to 1 bait pellet per m²), or 45 kg/ha (equivalent to 1.5 bait pellets per m², and listed in bold), as each pellet weighed 3.06 ± 0.09 g (n = 49).

Site No (see Fig. 1)	Site	Habitat description	Average & (Maximum) Canopy Height (m)	Slope (%)	Application 1 (Pellets/m²) (March 18, 2016)	Application 2 (Pellets/m²) (April 9, 2016)
1	Deflector #1 (coastline of Long Valley [L.V.])	Coastal; rocky with herb/grass	0.2 ± 0.1 (2.5 ± 0.4)	2.4 ± 0.8	1.6 ± 0.4	1.6 ± 0.3
2	Deflector #2 (coastline of West Valley [W.V.])	Coastal; sand with little to no vegetation	0.1 ± 0.0 (0.7 ± 0.3)	4.4 ± 2.2	0.6 ± 0.2	1.6 ± 0.4
3	Coastal Overlap #1 (50–80 m inland of high tide line, L.V.)	Mixed shrubland with herbs, grass, small trees	1.3 ± 0.2 (4.0 ± 0.1)	7.3 ± 1.5	**0.9 ± 0.2**	**1.2 ± 0.3**
4	Coastal Overlap #2 (50–80 m inland of high tide line, W.V.)	Thick grassland and scattered shrubs	0.7 ± 0.1 (3.0 ± 0.2)	4.4 ± 1.5	**1.8 ± 0.2**	**0.7 ± 0.3**
5	Valley Bottom #1 (L.V.)	Forest	3.3 ± 0.1 (7.0 ± 1.1)	15.4 ± 1.9	**0.8 ± 0.2**	**2.1± 0.4**
6	Valley Bottom #2 (W.V.)	Forest	3.5 ± 0.2 (9.3 ± 0.7)	18.4 ± 2.4	**1.4 ± 0.3**	**2.1 ± 0.4**
7	Ridge/Slope #1 (West Ridge of W.V.)	Forest edge and open shrubland	2.6 ± 0.3 (6.9 ± 0.7)	10.4 ± 2.4	1.2 ± 0.3	1.7 ± 0.3
8	Ridge/Slope #2 (Head-slope of L.V.)	Forest	3.1 ± 0.3 (7.8 ± 0.7)	8.0 ± 3.2	1.2 ± 0.3	1.3 ± 0.3
9	Ridge/Slope #3 (Ridge and slope of island peak)	Forest edge and open shrubland	2.3 ± 0.2 (5.4 ± 0.5)	28.1 ± 3.3	1.1 ± 0.2	0.9 ± 0.2
10	Ridge/Slope #4 (Slope of L.V. northwest wall)	Forest	4.2 ± 0.2 (10.4 ± 0.9)	19.6 ± 6.0	0.5 ± 0.2	0.9 ± 0.3
11	Cliff (northeast cliff and windward slope)	Windswept shrubland with herbs and grass	0.8 ± 0.1 (2.9 ± 0.2)	14.3 ± 4.8	**0.7 ± 0.2**	**1.7 ± 0.2**

bottoms, cliff, deflector, coastal overlap), the start of a transect was randomly established by blindly throwing an object over one's shoulder while standing on the walking trail and then beginning the transect from where the object landed. The 10 m interval flagging marked the location of the 1 m² plots for which we monitored bait pellets (15 1 m² plots per transect; 165 total plots for each application at all 11 sites).

A total of 15 trail cameras (12 Reconyx HyperFire models HC500 and HC600, and three Browning Model No: BTC-6HD) were placed to monitor bait pellets to help identify animals visiting and consuming the pellets. Each of the 11 sites always had at least one plot with a trail camera monitoring baits, and some sites had up to three cameras positioned at randomly assigned plots. Only one camera was placed per plot, and each camera was secured to the lower 30–70 cm of a tree or rock. Within 15–120 minutes of the helicopter applying bait to the site, two bait pellets were gathered from the surrounding 2 m² of a respective plot and the trail camera was aimed at the two bait pellets that were placed side-by-side, 40–90 cm away from the camera. A pin-flag was placed next to the two bait pellets in each plot so their presence could be monitored with subsequent visits. All other bait pellets in a 1 m diameter around the pin flag that marked the two target pellets were removed from the area so as not to confuse the observer monitoring pellets. The cameras were set to be triggered by motion, but also were programmed to take a picture each hour (on the hour), and sometimes more frequently (15 or 30 min) at set intervals to help account for periods where bait disappeared or was visited without an animal triggering the camera (e.g. insects rarely trigger these cameras). Once a Reconyx camera was triggered by motion, it would take 10 consecutive pictures over 20 seconds; Browning cameras would take one picture each time triggered.

Cameras were serviced (batteries and SD cards changed, checked for functioning) as needed, and if both bait pellets were removed from a plot with a motion-camera, the camera would be moved to another plot within the site, where bait pellets were still present. Upon activating the cameras on the day of each bait application, the baits and cameras were checked daily for at least seven consecutive days, which was the duration that field staff was on the island; the bait pellets and cameras were also checked at day 20 after the first application because that day preceded the second (and final) application and field staff had returned to the island.

For our analysis, we scored the number of incidences where an animal was observed contacting the bait (i.e. touching, eating, removing). An incidence ended when the animal left the camera's field of view, or when a series of pictures produced by one triggering event ended. The trail cameras monitored for 27 continuous days, which began the first day of application one and ended seven days after application two. Results were presented in three time-periods: 1) application one until the date rats were last observed contacting bait (i.e. day five), 2) days 6–20 post-application one, and 3) the first seven days following application two.

RESULTS

From the 15 cameras deployed, ~38,000 pictures were taken between application one and two (i.e. 20 days of continuous monitoring). We reviewed each picture from all 11 sites, and found 2,686 pictures where an animal was present. Most of the pictures that captured animals showed that they were not in contact with the bait, but instead they were passing by the bait (e.g. ameiva in Fig. 2), or perhaps searching or foraging nearby the bait. Seventy pictures from application one showed an animal in contact with a bait pellet. The first five days following application one was the only time period that rats were observed in contact with the bait (18–22 March), and of the 40 pictures involving animals during this period, 20 were of individual rats (Fig. 3). Although rats dominated bait contact (Fig. 4) during the first five days following bait application (especially so during the first two days), hermit crabs (Fig. 5) comprised 32% of bait contact events (Fig. 3). Most rats and hermit crabs contacting bait either removed it or consumed it in place. Ameivas, which contacted the bait in 13% of the pictures during the first five days, usually had a part of their body (e.g. leg, tail) contacting the bait, or they occasionally touched it with their snout, or on one occasion licked the bait and moved out of the frame. Thus, other than a single lick of the bait, ameivas were never seen consuming (biting, chewing, swallowing) or removing the bait. Finally, there were two insects (one appeared to be a grasshopper) seen in contact with a bait pellet during the first five days following bait application one (Fig. 3).

The last day when a rat was captured by motion-cameras on Desecheo was 23 March, which was the sixth day following application one. On this day, there was one rat pictured at Coastal Overlap #2 (grass/shrubland), and one at Ridge #2 (forest). Neither rat came into contact with the bait, but instead passed within 12 cm and 1 m of the bait pellets. These were the last two rats pictured by trail cameras on Desecheo despite the cameras being active and bait present in their field of view through to 15 April 2016.

There were 30 pictures from days 6–20 (23 March–7 April) following application one that showed an animal

Fig. 2 An adult ameiva (*Ameiva desechensis*) triggers a trail camera positioned to monitor brodifacoum bait pellets on Desecheo Island, March 2016. Notice the two green bait pellets at the base of a pin-flag at the lower central position of the photo. Ameivas rarely were pictured in contact with the bait and were never documented consuming or removing the bait pellets.

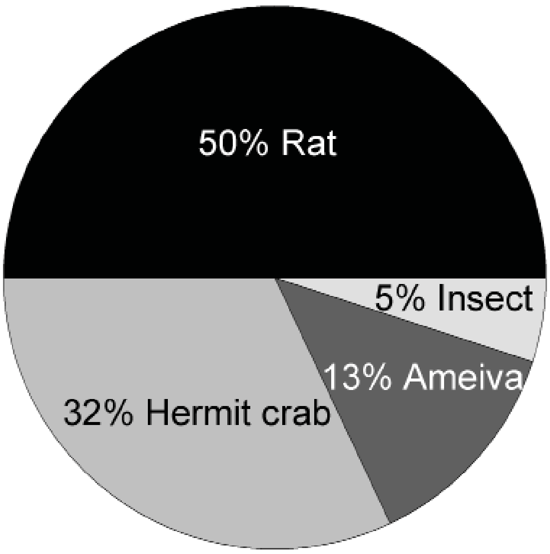

Fig. 3 Percentage of all trail camera results when an animal was in contact with a bait pellet (e.g. touching, eating, removing) during the first five days (18–22 March) after bait application one, on Desecheo Island, Puerto Rico. There was a total of 40 animals in contact with bait during this period (20 rats, 13 hermit crabs, five ameivas, and two insects), and these pictures were taken on the following five sites (Cliff, Overlap #2, Deflector #1, Ridge #4, and Long Valley #1; see Table 1 for site descriptions).

Fig. 4 A black rat (*Rattus rattus*) triggers a trail camera positioned to monitor brodifacoum bait pellets on Desecheo Island, March 2016. Notice the bait pellet the rat is nearly touching with its nose. Black rats, being the target species, were pictured consuming and removing the bait pellets for the first five days following the first bait application (18 March 2016).

Fig. 5 A hermit crab (*Coenobita clypeatus*) triggers a trail camera while approaching a bait pellet on Desecheo Island. Hermit crabs were the primary visitors and consumers of bait pellets after the first week following application one.

in contact with a bait pellet. Because rats were no longer present or otherwise not pictured by the trail cameras, the proportion of animals documented contacting the bait shifted (compare Fig. 3 and Fig. 6), such that hermit crabs comprised nearly half (i.e. 14 of 30) of the pictures, and ameivas were pictured contacting the bait in 37% of the pictures during this period (Fig. 6). Insects, primarily grasshoppers, were contacting the bait in four pictures, and there was one picture of a black land crab (*Gecarcinus ruricola*) consuming a bait pellet during this period (Figs 6 & 7).

Sites tended to differ in the types of animals, and their relative abundances, captured on camera contacting bait pellets. In total, there were only five sites following application one that had pictures of animals contacting bait, even though all 11 sites had one to three cameras monitoring bait pellets and all 11 sites had pictures of some animals in the view. For example, the Cliff site only had pictures of hermit crabs contacting bait, whereas the Deflector #1 site only had pictures of insects (primarily grasshoppers) contacting bait (Fig. 8). Coastal overlap #2 and Deflector #1 were the only sites that had rats pictured contacting bait, and Long Valley #1 (valley bottom) and Coastal Overlap #2 were the only sites that had ameivas pictured contacting the bait pellets following application one (Fig. 8). It should be noted here that trail cameras were only monitoring, although continuously, a small subset of the total bait applied to Desecheo (i.e. only about 30 baits; 15 cameras monitoring two baits each).

Bait pellets were monitored during the first seven days following bait application two (Day 21–27), which occurred on 9 April 2016. There were approximately 31,000 pictures taken and reviewed during this period, and 176 pictures contained an animal. Similar to our findings after the first application, most of the pictures that captured animals showed that they were not in contact with the bait. There were 16 incidences where animals were in contact with bait pellets during the week following application two. There tended to be few proportional changes in animal-bait interactions that occurred from the 6–20 days of monitoring after bait application one and the first seven days of bait application two (Day 21–27). Hermit crabs continued to dominate bait interactions, and insect consumption of the bait had risen to the highest proportional levels of all previous measurements (Fig. 9). Ameiva interactions tended to decrease after application two relative to the 6–20 days following application one (Fig. 9). There were five incidences of animals contacting bait pellets during days six and seven: two hermit crabs, two insects, and one ameiva; thus, the first five days of bait interaction would have been similar to the first seven days of bait interaction. Furthermore, the pictures that captured animals interacting with bait occurred at five of the 11 sites (Cliff, Overlap #1, Ridge #1, Ridge #4, and Long Valley #1) during the week following bait application two. As

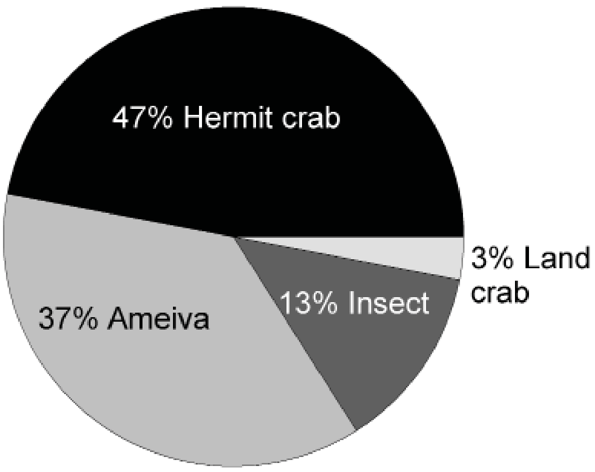

Fig. 6 Percentage of all trail camera results when an animal was in contact with a bait pellet (e.g. touching, eating, removing) during days 6–20 (23 March-7 April) following bait application one, on Desecheo Island, Puerto Rico. There was a total of 30 animals in contact with bait during this period (14 hermit crabs, 11 ameivas, four insects, and one black land crab), and these pictures were taken on the following five sites (Cliff, Overlap #2, Deflector #1, Ridge #4, and Long Valley #1; *see Table 1 for site descriptions*). Note that there were no rats pictured interacting with bait after five days, and rats were not pictured at all after six days following bait application one.

Fig. 7 A black land crab (*Gecarcinus ruricola*) triggers a trail camera while consuming a bait pellet on Desecheo Island. Black land crabs were rarely observed, and only active at night, on Desecheo Island.

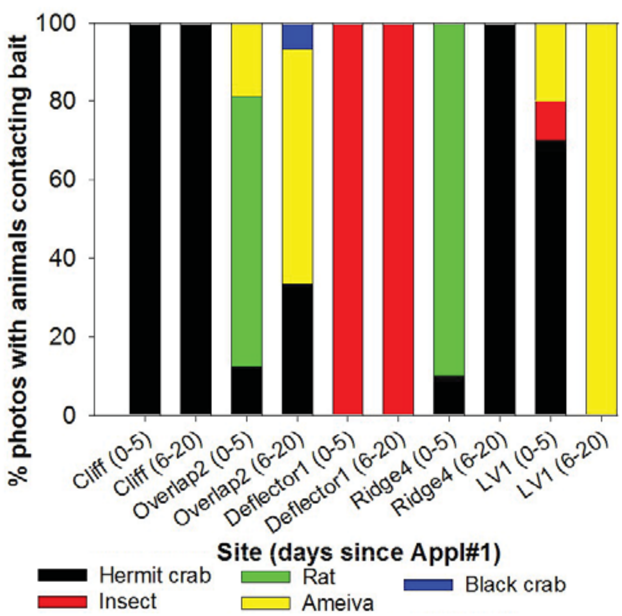

Fig. 8 Percentage of all trail camera results, separated by site, depicting when an animal was in contact with a bait pellet (e.g. touching, eating, removing) during the initial five days (18–22 March), and days 6-20 (23 March-7 April), following bait application one, on Desecheo Island, Puerto Rico. There was a total of 70 animals in contact with bait during this period (i.e. 40 during the initial five days, 30 from 6–20 days), and these pictures were taken at the following five sites (Cliff, Overlap #2, Deflector #1, Ridge #4, and Long Valley #1; *see Table 1 for site descriptions*). Note that there were no rats pictured interacting with bait after five days, and rats were not pictured at all after six days following bait application one.

with all previous pictures, hermit crabs and insects were observed consuming bait pellets, yet ameivas were not seen consuming bait.

DISCUSSION

Trail camera usage during the 2016 rat eradication on Desecheo Island allowed us to quantify, in near "real-time" fashion, the proportional visitation, removal, and consumption of bait pellets, and the timing of such visitation, by target rats and non-target species. Such quantification of bait interactions allows for upscaling to whole habitats and an island-wide understanding of the risks to non-target native species and the potential effectiveness of the eradication campaign at various timescales following initial bait application. Initially, most bait interactions involved rats, and the last rat documented by cameras was on the sixth day after initial bait application. Non-targets that consumed, removed, or otherwise contacted the bait pellets were numerous during the continuous 27 days of cameras monitoring bait pellets on Desecheo, and hermit crabs, ameiva lizards, and insects were the main non-target visitors to the bait pellets. Trail camera usage can therefore better inform rodent removal campaigns of potential animal exposure pathways and confirm target bait acceptance as they are occurring, and therefore should be considered for future rodent control and eradication operations.

Trail cameras revealed that bait was readily consumed by invasive rats on Desecheo during the 2016 rat eradication campaign. Results during the first five days following bait application, when averaged across all monitored habitats, revealed half of the bait that animals on Desecheo interacted (i.e. made contact) with was by rats, and these were most-likely bait consumption events. Without implementing trail cameras to monitor bait pellets, our sole indication that rats were consuming the bait would have not occurred until four days post-application when the first rats turned up dead (Shiels, et al., 2017a). Live rats were rarely observed during the day prior to and following bait application, and bait was never observed being visited by rats without the aid of trail cameras (Shiels, et al., 2017a). Furthermore, carcasses of rats may not always be found because of the expense to keep monitoring crews on the island for extended periods following bait application, rodents suffering from toxicosis often die belowground, and dead rats are quickly scavenged on many islands with a substantial land crab population (Pitt, et al., 2015). Although non-toxic bait uptake trials using biomarkers were performed prior to the 2012 rat eradication attempt on Desecheo (USFWS, 2011), trail cameras provided evidence during the 2016 rat eradication that rats were indeed consuming the bait.

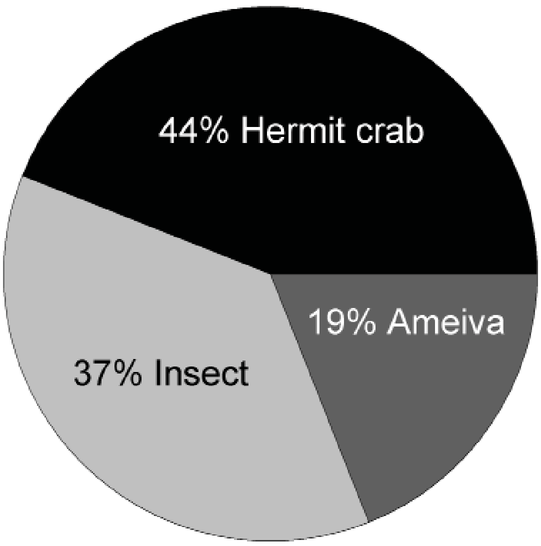

Fig. 9 Percentage of all trail camera results when an animal was in contact with a bait pellet (e.g. touching, eating, removing) during days 0–7 (9–16 April) following bait application two, on Desecheo Island, Puerto Rico. There was a total of 16 animals in contact with bait during this period (seven hermit crabs, three ameiva, six insects), and these pictures were taken at the following five sites (Cliff, Overlap #1, Ridge #1, Ridge #4, and Long Valley #1; *see Table 1 for site descriptions*).

If we use the trail camera findings to scale-up to the whole island, and assume that all pictures with rats contacting the bait resulted in the bait pellet being consumed by the rat, over half of the 5,325 kg of bait that was distributed across Desecheo in application one, and most (or all) of the 5,325 kg of bait in application two, was not consumed by rats. Furthermore, > 75% of the bait applied to Desecheo was consumed by non-target species or did not result in animal consumption (i.e. the bait disintegrated into the soil or was consumed by the microbial community). Clearly, accounting for non-target bait consumption is a critical part of the best practices associated with initial determination of bait application rates for island-wide rat eradications (Pott, et al., 2015). For example, six- to eight-times as much bait as the Brodifacoum 25W: Conservation parent label includes was applied to Palmyra Atoll, in the tropical Pacific, to account for the high density of land crab populations (Pitt, et al., 2015). Land crabs are a well-known non-target species that, like all other invertebrates, are not affected by the brodifacoum toxicant when they consume the bait, but they render the bait unavailable to target rodents (Cuthbert, et al., 2012). Our evidence from trail cameras during the Desecheo rat eradication demonstrates how common non-target bait interactions can be when rodenticides, such as brodifacoum bait pellets, are used for rodent removal. Furthermore, trail cameras revealed the importance of applying additional bait to Desecheo to account for non-targets, primarily hermit crabs, rendering the bait pellets unavailable to rats.

Substantial spatial variation of rat and non-target bait pellet interactions was present during the period following bait application on Desecheo, as bait interactions involving particular animal species tended to differ by habitat (Fig. 8). We must remind the reader that only a very small subset of the bait pellets applied to Desecheo were monitored with trail cameras, and there were far more appearances of animals in the camera view than there were animals that contacted the bait pellets. Additionally, several of the sites that had trail cameras continuously monitoring bait pellets did not have any rats that contacted the bait pellets. The spatial heterogeneity of rat and non-target events in various habitats also highlights the need for trail camera replication, and we feel that our sample size of 15 cameras is modest, and that substantially fewer cameras would be insufficient for an island of size and habitat heterogeneity like Desecheo. Additionally, we benefited from programmed interval-triggering for the cameras that supplemented motion-triggering because this helped capture insects and other small or slow-moving animals that would not trigger the cameras (Newey, et al., 2015). However, the trade-off of programmed interval-triggering, and 10 pictures per triggering, is the added human labour needed to view and analyse the large number of pictures.

Temporal variation of target rodent visitors to bait pellets can inform operational use of the rodenticide, and the trail cameras revealing an absence of rats after six days on Desecheo may suggest modifications to the operation plan to shorten the length of bait availability on the island. However, adjustments to operational plans are generally made to be more conservative (i.e. more bait for longer periods) rather than less conservative.

Our concerns of primary brodifacoum bait exposure to the Desecheo endemic lizard community were abated by the trail camera results, as there was an absence of pictures where lizards were observed consuming bait despite their interactions with the pellets. Additionally, there were no population level impacts to the lizard community as observed by the mark-and-recapture work completed in 2012 (Herrera Giraldo, et al., 2019). Ameivas were the only lizard species that were pictured in contact with the bait pellets during our monitoring, and there was no evidence of bait consumption aside from a single lick of the bait pellet by one individual. Most events where ameivas contacted the bait were by brushing the tail or legs on the pellet when passing by. Ameivas, and the other lizard species on Desecheo, are primarily insectivorous, and are commonly seen foraging in the leaf litter for insects (Shiels, et al., 2017a). Based on brodifacoum residue analysis following bait application, all three endemic lizard species had detectable levels of brodifacoum in their livers or bodies (Shiels, et al., 2017a), and the trail cameras and general diets of these lizards support consumption of contaminated insects as the most-likely pathway for such brodifacoum exposure. Although we could not definitively conclude that insects pictured on the bait pellets were consuming them, at minimum they would have gained exposure to the bait through direct contact, which probably facilitated exposure to higher trophic level predators. We were surprised that birds, particularly pearly-eyed thrashers (*Margarops fuscatus*), were not pictured consuming bait pellets as the few birds collected for residue analysis had evidence of brodifacoum exposure (Shiels, et al., 2017a); however, their omnivorous diet that includes invertebrates and vertebrates (Wetmore, 1916) favours brodifacoum exposure through this secondary pathway.

Trail cameras are a cheaper method than residue analysis to document primary exposure of target and non-target species during rodenticide campaigns. The USDA NWRC Chemistry Unit commonly charges between US$150–US$250 per sample for brodifacoum residue analysis, and this is a comparable fee to other laboratories. Additionally, brodifacoum residue analysis generally takes several weeks to complete. There is a wide price range in trail cameras, but some of the least expensive trail cameras can be purchased for <US$100 per camera (e.g. see https://www.amazon.com/). Inexpensive trail cameras are often adequate for most rodent removal campaigns because these cameras produce an image that is identifiable as a rat or a non-target (e.g. Bushnell brand from 2005 used in Shiels & Drake (2011)); the reliability, quality of the image, and flexibility of the cameras in customising image quality, triggering frequency, and sensitivity are all factors that are generally better in the Reconyx Hyperfire cameras (US$450–US$550 for those used in our study; http://www.reconyx.com/product/Outdoor_Series) than the less expensive alternatives (see Newey, et al. (2015) for a review). An important component that trail cameras cannot easily produce is evidence of secondary exposure of non-target species. One could, however, position rodent carcasses (or non-target carcasses of interest) on the ground such that trail cameras could document the scavengers of those carcasses. The potential brodifacoum exposure of local raptors is worrisome (e.g. Rueda, et al., 2006), and on Desecheo there are only a few resident kestrels, and several non-resident raptor visitors (several species of hawks), that would not be easily observable in their consumption of carcasses or any mortalities that may occur from rodenticide exposure on Desecheo.

Prior to rodenticide use, trail cameras can also help in surveying the potential target and non-target species at a site. Either singly or in combination with non-toxic bait uptake trials (Pott, et al., 2015), trail cameras can inexpensively help identify the potential animals without catching or harming them. Because rodenticide bait pellets are a mostly cereal-grain matrix, setting out 'home-made' mixtures or placing local fruits and seeds on the ground with monitoring cameras (*see* Shiels & Drake, 2011) may be a first step in determining some of the potential animal species that may visit rodenticide baits. This may be applicable for planning purposes, especially on isolated islands where visits to the island may be short or infrequent. Additionally, advanced trail camera technology now allows pictures to be checked remotely, via cellular transmission of the pictures to a cell phone or email account (Eason, et al., 2017).

Additional benefits of using trail cameras include assistance in the confirmation that the target rodent species is indeed the only rodent species on the island. Trail cameras producing high quality pictures, and multiple shots that can reveal multiple angles of the animal, allow for distinguishing features (e.g. tail length, ear size, body size) to be revealed and assessed. Furthermore, there are some occasions where rat-eradications have resulted in surprises such as house mouse populations 'suddenly present', or an explosion in their abundance, due to the mice being masked by the dominance of rats prior to rat eradication (Witmer, et al., 2007); trail cameras would be a viable method to document and act upon such surprises. Trail cameras may also be implemented to assess the particular prey (e.g. fruit and seed) that are most attractive or vulnerable to rodent predation (e.g. Shiels & Drake, 2011), and to document biological change after rodent removal by quantifying before and after native prey survival (e.g. Pender, et al., 2013). On Desecheo, there was a major caterpillar outbreak coinciding with rat removal (Shiels, et al., 2017b), and trail cameras could have been used to better document the development of the outbreak.

The use of trail cameras is an underutilised method of risk assessment for rodenticide use, particularly assessing primary rodenticide exposure that could be a substitute for, or an improvement upon, more expensive methods that require animal handling or sacrifice. Trail cameras can be placed across a variety of habitats, installed to monitor bait for extensive periods (days to months), and reliably record diurnal and nocturnal visitation of target and non-target animals while not substantially altering behaviours or harming resident animals. Trail cameras provide temporal and spatial information regarding the effectiveness of rodent removal, help inform the hazards of rodenticide use, and can be easily incorporated into rodent removal operations.

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